THEMIS observations of a transient event at the magnetopause

G. I. Korotova,[1,2] D. G. Sibeck,[3] A. Weatherwax,[4] V. Angelopoulos,[5] and V. Styazhkin[1]

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[1] This study focuses on Time History of Events and Macroscale Interactions During Substorms (THEMIS) observations of a long-duration transient event in the vicinity of the dayside magnetopause at ~15:34 UT on 18 July 2008 that was characterized by features typical of a magnetospheric flux transfer event (FTE): a bipolar negative-positive 5–7 nT signature in the Bn component, a positive monopolar variation in the Bl and Bm components, a ~5–7 nT enhancement in the total magnetic field strength, and a transient density and flow enhancement. The interplanetary magnetic field (IMF) was mostly radial and disturbed during the intervals studied; that is, it was favorable for the repeated formation, disappearance and reformation of the foreshock just upstream from the subsolar bow shock. We show that varying IMF directions and solar wind pressures created significant effects that caused the compressions of the magnetosphere and the bow shock and magnetopause motions and triggered the transient event. Global signatures of magnetic impulse events (MIEs) in ground magnetograms during the period suggest a widespread pressure pulse instead of a localized FTE as the cause of the event in the magnetosphere. The directions of propagation and the flow patterns associated with the event also suggest an interpretation in terms of pressure pulses.

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1. Background and Objective

[2] The bewildering variety of transient signatures observed at the dayside magnetopause and in the magnetosphere provides substantial evidence indicating that the solar wind-magnetosphere-ionosphere interaction is unsteady. There are at least four possible causes for the transient events: boundary waves driven by solar wind, or foreshock-generated, dynamic pressure variations [e.g., *Sibeck et al.*, 1989; *Farrugia et al.*, 1989], unsteady magnetopause merging [e.g., *Russell and Elphic*, 1978; *Lee and Fu*, 1985], the Kelvin-Helmholtz (KH) instability [e.g., *Southwood*, 1979; *Junginger and Baumjohann*, 1988] and impulsive plasma penetration [e.g., *Lemaire*, 1977; *Lundin*, 1988; *Heikkila*, 1990]. Models for each mechanism predict transient events with different occurrence patterns and signatures as a function of solar wind conditions. Whether or not magnetic reconnection or wavy magnetopause motion due to a solar wind pressure variations or the KH instability causes transient events is central to understanding the transport of plasma and magnetic flux from the dayside to the nightside magnetosphere. Flux transfer events have attracted considerable attention for the last 30 years because transient reconnection may be the main mode of solar wind–magnetosphere interaction [*Lockwood et al.*, 1995].

[3] With respect to occurrence patterns, model predictions include the notions that the reconnection generating FTEs is most likely on the dayside magnetopause during periods of southward IMF orientation [e.g., *Rijnbeek et al.*, 1984; *Le et al.*, 1993] and that kinetic processes in the foreshock generate pressure pulses in response to abrupt IMF changes toward or away from the radial direction [e.g., *Fairfield et al.*, 1990; *Sibeck and Korotova*, 1996]. Large velocity shears transverse to both magnetosheath and magnetospheric magnetic fields and high densities favor the KH instability on the flanks of the magnetosphere during intervals of high solar wind velocity [e. g., *Southwood*, 1968]. Impulsive penetration is posited upon the existence of filamentary solar wind structures that reach and penetrate the magnetopause with enhanced momentum. The possibility of impulsive penetration has been disputed by *Cowley* [1986] and *Owen and Cowley* [1991]. Though *Echim and Lemaire* [2005] recently refined solutions for the sheared flow of collisionless plasma across magnetic field lines in a kinetic model, impulsive penetration is rarely invoked to explain transient events in the magnetosphere.

[4] Some of the signatures predicted by the various models are similar, while others are different [e. g., *Sibeck and Smith*, 1992; *Elphic*, 1995]. FTEs are identified primarily by bipolar variations in the magnetic field component Bn normal to the nominal magnetopause, but also by magnetic field strength enhancements, bursts of enhanced velocities, and mixtures of magnetospheric and magnetosheath plasma [*Russell and*

[1]IZMIRAN, Troitsk, Russia.
[2]Also at IPST, UMD, College Park, Maryland, USA.
[3]NASA GSFC, Greenbelt, Maryland, USA.
[4]Department of Physics and Astronomy, Siena College, Loudonville, New York, USA.
[5]IGPP, ESS, UCLA, Los Angeles, California, USA.

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Elphic, 1978; *Paschmann et al.*, 1982]. *Berchem and Russell* [1984] and *Rijnbeek et al.* [1984] showed that "standard" positive-negative Bn signatures tend to occur north of the ecliptic equator, and "reverse" negative-positive signatures tend to occur south of it. *Dailey et al.* [1985] showed that "standard" ("reverse") Bn signatures are found almost exclusively for FTEs traveling northward (southward).

[5] *Farrugia et al.* [1987] modeled the magnetic field and plasma flow perturbations generated by a two-dimensional cylinder moving along the magnetopause surface. *Papamastorakis et al.* [1989] employed a technique developed by *Sonnerup and Wang* [1987] to determine the orientation and motion of FTEs observed by AMPTE IRM. *Elphic* [1995] used plasma, magnetic field, and energetic particle signatures observed by the low-latitude and mid-latitude ISEE and AMPTE spacecraft to identify four classes of magnetosheath and magnetospheric FTEs. The impact parameter, or distance of the spacecraft pass from the center of the event, determines which signature is observed. For example, flows inside FTEs are in the direction of event motion, those outside are opposite [*Sibeck and Smith*, 1992; *Korotova et al.*, 2009].

[6] FTEs are not the only features that produce Bn signatures and plasma flows. *Sibeck et al.* [1989] and *Sibeck* [1990] argued that wavy magnetopause motion driven by solar wind dynamic pressure variations might produce signatures similar to those observed during FTEs. *Sibeck* [1992] showed that several events previously identified as FTEs exhibited all the characteristics expected for antisunward moving magnetopause waves.

[7] There are some signatures which may help to distinguish between FTEs and pressure variation driven boundary waves [*Song et al.*, 1994; *Otto*, 1995]. All models predict that the majority of events move antisunward. According to the reconnection model, transient events form along equatorial reconnection lines passing through the subsolar magnetopause. Those on the subsolar magnetopause on magnetic field lines rooted in the northern ionosphere should move dawnward during periods of duskward IMF (By >0), but duskward during periods of dawnward IMF (By <0) [*Cowley and Owen*, 1989]. The sense of motion reverses for events on magnetic field lines rooted in the southern ionosphere. According to the pressure pulse model, events move dawnward across local noon during periods of spiral IMF orientation and duskward during periods of orthospiral IMF orientation [*Sibeck*, 1990]. The locations where the events originate and their direction of motion can therefore distinguish between events generated by the pressure pulse and bursty merging models.

[8] Statistical surveys of transient events with clear bipolar Bn signatures observed by the AMPTE CCE [*Sanny et al.*, 1996] and geosynchronous spacecraft [*Sanny et al.*, 2001], indicating that enhanced event occurrence rates prior to local noon (downstream for the foreshock during intervals of typical spiral IMF) and motion is antisunward; correspondences with upstream features show that many events were generated by pressure pulses.

[9] Spatial extents can help distinguish between events generated by solar wind dynamic pressure changes and bursty reconnection. Bursts of transient reconnection extend over only a small portion of the magnetosphere [*Russell and Elphic*, 1978] and couple to the ionosphere through transverse Alfvén waves, thereby producing spatially localized magnetospheric signatures. By contrast, solar wind dynamic pressure changes strike the entire magnetosphere, producing signatures in ground magnetometers from high to low latitudes and all longitudes [*Sibeck and Korotova*, 1996].

[10] *Kawano et al.* [1992] surveyed transient magnetic variations in the dayside magnetosphere observed by AMPTE CCE and demonstrated that the sense of east/west magnetic field perturbation generated by FTEs depends on GSM latitude and MLT. Although the events were scattered from L = 6 to 9.5, those with larger amplitudes were observed closer to the magnetopause. They concluded that pressure pulses are the dominant cause of transient events with longer durations (>1.5 min), whereas magnetic merging and FTEs are the dominant cause of transient events with shorter durations.

[11] *Kim et al.* [2001a, 2001b] studied a series of transient events with bipolar signatures observed by Geotail. *Kim et al.* [2001a] showed that the transient events might be explained by magnetopause motion due to compression or expansion of the magnetosphere caused by solar wind or foreshock pressure variations hitting the magnetopause while *Kim et al.* [2001b] demonstrated that the characteristics of the transient disturbances were consistent with the passage of a train of flux transfer events propagating tailward.

[12] Furthermore, a number of papers indicate that deformations of the magnetospheric boundary driven by the KH instability can generate significant Bn signatures [e.g., *Nykyri et al.*, 2003]. *Nykyri and Otto* [2001] showed that the vortex motion driven by the KH instability can lead to antiparallel magnetic field components at strong and thin current layers, in turn driving reconnection. *Nykyri at al.* [2003, 2006] reported that the KH instability and FTE generation can be distinguished by evaluating satellite data using the Walén relation, testing for the de Hoffman-Teller frame and performing a vector variance analysis.

[13] *Eriksson et al.* [2009] proposed that small-scale FTEs characterized by enhanced total plasma pressures centered on bipolar Bn features may be generated during the early growth phase of the KH instability due to pulse-like low-shear reconnection between magnetosheath and magnetospheric fields on the trailing edges of the growing KH surface waves.

[14] Determining which mechanism accounts for any individual event or is most typical requires correlated data sets including multi-instrument solar wind and magnetospheric observations. As predicted [*Sibeck and Angelopoulos*, 2008], the well-instrumented simultaneous multispacecraft Time History of Events and Macroscale Interactions During Substorms (THEMIS) measurement of the bow shock, magnetopause, magnetosheath and the dayside magnetosphere with a string of pearls orbit near the ecliptic plane prove essential in distinguishing between the predictions of the models for transient events. Several papers have presented THEMIS observations of FTEs [e.g., *Angelopoulos et al.*, 2008; *Sibeck et al.*, 2008; *Liu et al.*, 2008; *Fear et al.*, 2009], KH instabilities [e.g., *Agapitov et al.*, 2009; *Eriksson et al.*, 2009] and large amplitude boundary motion [*Suvorova et al.*, 2010]. Here we present observations of FTEs that can be demonstrably shown to be boundary waves driven by pressure pulses, generated in the immediate vicinity of the bow shock and absent in the solar wind.

[15] Our study focuses on THEMIS A, D, E observations of a long-duration transient event in the vicinity of the

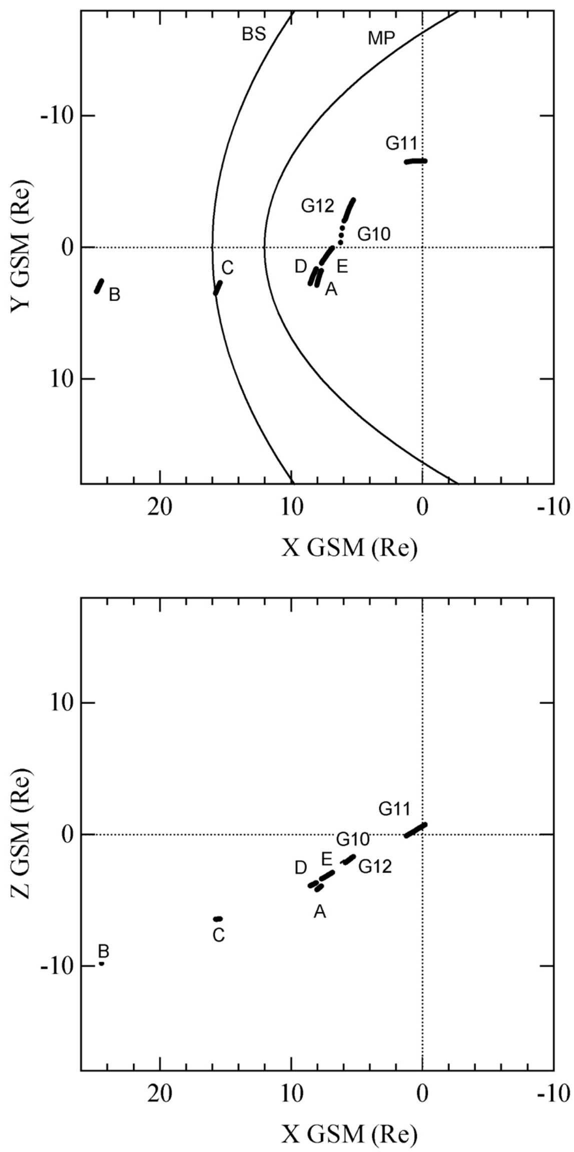

Figure 1. Locations of THEMIS A, B, C, D, E and GOES 10/11/12 in the GSM X-Y and X-Z planes from 15:00 to 16:00 UT on 18 July 2008. The locations of the bow shock and magnetopause were chosen for the real solar wind conditions (Bz = 0 nT, Pdyn = 0.5 nPa).

dayside magnetopause at ~1534 UT on a quiet day of 18 July 2008. We seek to determine whether this transient event, which satisfies classic FTE criteria is a true FTE or a boundary wave/impulsive event with bipolar magnetic field fluctuations normal to the nominal magnetopause produced by the KH instability or pressure pulses. These impulsive events correspond to well-known magnetic impulse events (MIEs) in ground magnetograms. Attributing transient events to their source provides important information concerning the dynamic processes on the magnetopause.

2. Data Sets, Spacecraft, Orbits

[16] The five THEMIS spacecraft carry identical high-heritage instruments. The ESA electrostatic analyzer on each THEMIS spacecraft measures the distribution functions of 0.005 to 25 keV ions and 0.005 to 30 keV electrons over 4π-str, providing accurate high time resolution plasma moments, pitch angle and gyrophase particle distributions as often as 3 s each [*McFadden et al.*, 2008a]. The FGM triaxial fluxgate magnetometer measures the background magnetic field and its low-frequency fluctuations up to 64 Hz [*Auster et al.*, 2008]. The spacecraft return magnetic field vectors, omnidirectional particle spectra, and plasma moments computed on board once every 3 s throughout their orbit. During 50% of each orbit they also return full angular resolution ESA and SST particle distribution functions at spin resolution (3 s). We compare the THEMIS observations with geosynchronous magnetic field observations with 0.5 s time resolution [*Singer et al.*, 1996]. Ground magnetometer data were available with 0.5 s time resolution for the stations in the THEMIS database, 1 s time resolution from the Antarctic stations and 20 s time resolution from the Greenland network.

3. Spacecraft Observations

[17] The day of 18 July 2008 was a quiet day with sum of Kp indices only equaling 6. There were no geomagnetic storms, Dst index exhibited minor variations from −6 nT to −13 nT and AE index did not exceed 40 nT for the interval under study. ACE and Wind were both located some 200 R_E upstream from Earth at the L1 libration point where they observed similar plasma parameters (solar wind dynamic pressure P ~ 0.4–0.7 nPa, velocity V = 380 km/s) but very different magnetic field orientations (not shown). Figure 1 shows the location of THEMIS D, A and E that moved outbound from 15:00 to 16:00 UT through the early postnoon magnetosphere at slightly southern latitudes from GSM (X, Y, Z) = (8.10, 1.62, −3.65) R_E to (8.56, 2.75, −3.88) R_E, from (7.71, 1.76, −3.91) R_E to (8.05, 2.86, −4.18) R_E and from (6.86, 0.03, −2.87) R_E to (7.6, 1.19, −3.36) R_E, respectively. The location and shape of the magnetopause have been taken from the empirical study of *Roelof and Sibeck* [1993] for the real solar wind dynamic pressure of 0.5 nPa and IMF Bz = 0, while the subsolar bow shock location some ~4 R_E upstream from the magnetopause is simply scaled from that determined by *Fairfield* [1971] according to the sixth root of the solar wind dynamic pressure. For the observed solar wind conditions, THEMIS A, D and E should have been located deep within the magnetosphere, THEMIS C near the bow shock and THEMIS B in the solar wind.

[18] Figures 2 and 3 present the THEMIS A and D observations of magnetic field and plasma in boundary normal coordinates from 15:00 to 16:00 UT. Boundary normal coordinates were introduced by *Russell and Elphic* [1978] to study the magnetopause. Here N is the normal to the magnetopause, points outward along the magnetopause boundary normal, L points northward along the projection of Z component on the plane tangential to the magnetopause, and M completes the right hand orthogonal system and points westward (dawnward). To convert the THEMIS data into the boundary normal coordinates, we used the *Roelof and Sibeck* [1993] model magnetopause for the real solar wind conditions.

[19] As indicated in Figures 2 and 3, at ~15:34 UT, THEMIS A (GSM latitude $\Phi = -26.3°$, radial distance R_E = 9.22) and D ($\Phi = -23.7°$, R_E = 9.47) observed a long-duration

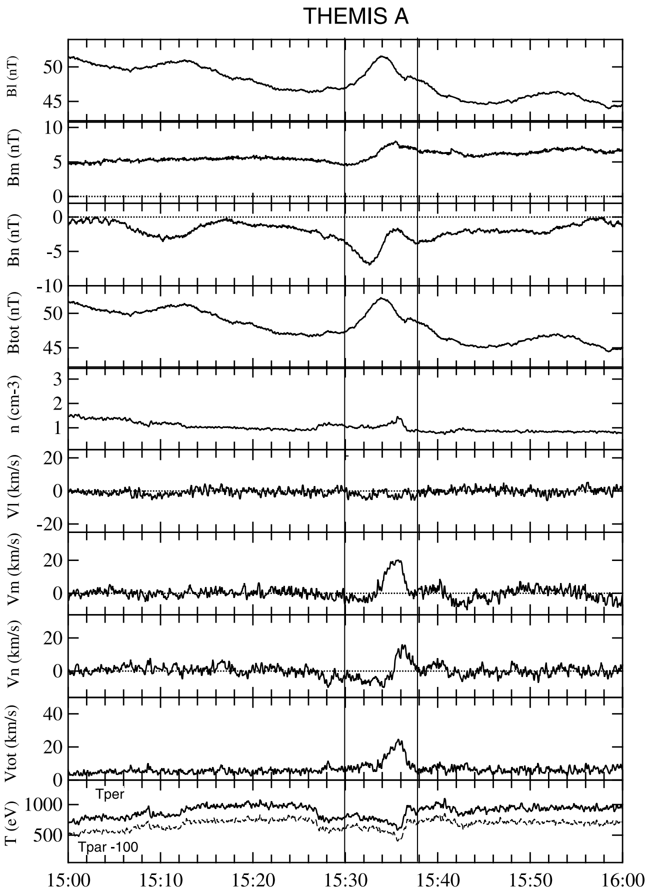

Figure 2. THEMIS A observations of plasma and magnetic field from 15:00 to 16:00 UT on 18 July 2008. From top to bottom, the Bl, Bm, Bn components of magnetic field in boundary normal coordinates, total magnetic field (Btot), the ion density (n), the velocities in boundary normal coordinates (V1, Vm, Vn, Vtot), and the ion temperatures (T) perpendicular and parallel to magnetic field are shown. The vertical lines bound the interval when the transient event was observed.

(~5 min) transient event with magnetic field perturbation characteristic of FTEs deep in the magnetosphere [*Elphic*, 1995]: a bipolar negative-positive 5–7 nT signature in the Bn component, a positive monopolar variation in the Bl and Bm components and a ~5–7 nT enhancement in the total magnetic field strength. The plasma observations also show features typical of a magnetospheric FTE: an increase in density, decrease in temperature, southward (−Vl) and dawnward (+Vm) flows, an asymmetric bipolar (negative, positive) variation in the Vn component, and an ~30–40 km/s increase in the total velocity. Note that the absolute values of the density and the velocity should be treated cautiously; during this interval there are issues with spacecraft charging and photoelectrons. Consistent with expectations, THEMIS D, closest to the magnetopause, saw stronger magnetic field and plasma signatures. Although both the FTE and pressure pulse models predict either correlated or anticorrelated velocity and magnetic field strengths [*Sibeck and Smith*, 1992], in this case the plasma signatures occur 2 min later than those in the magnetic field. Careful inspection indicates this is not a timing issue. Enhanced magnetospheric velocities enable the ESA instrument to observe the cold dense background ion plasma [*McFadden et al.*, 2008b], resulting in a density peak at the maximum velocity on the trailing edge of the transient event. THEMIS A and D observed weaker compressions of the total magnetic field at 15:12 and 15:53 UT.

[20] Figure 4 shows THEMIS E ($\Phi = -23.2°$, $R_E = 8.03$) observations of magnetic field and plasma parameters in boundary normal coordinates from 15:00 to 16:00 UT. THEMIS E, located deeper in the magnetosphere and closer to local noon than THEMIS A and D, observed a transient event with similar magnetic field features but an amplitude of only 5 nT. Located further than 4 R_E away from the magnetopause, it did not observe any special plasma signatures at the time of the transient event. According to the taxonomy, proposed by *Elphic* [1995], THEMIS E observed an FTE of category of A′, being farthest from the magnetopause, and THEMIS A and D observed FTEs of category B′. The peak of the transient total magnetic field disturbance at THEMIS E led that at THEMIS D by 59 s. To calculate the velocity at which the transient event propagated from THEMIS E to THEMIS D, we used the lag time and the azimuthal distance of ~9.8° separating the two satellites. The (duskward) propagation velocity of the transient event from THEMIS E

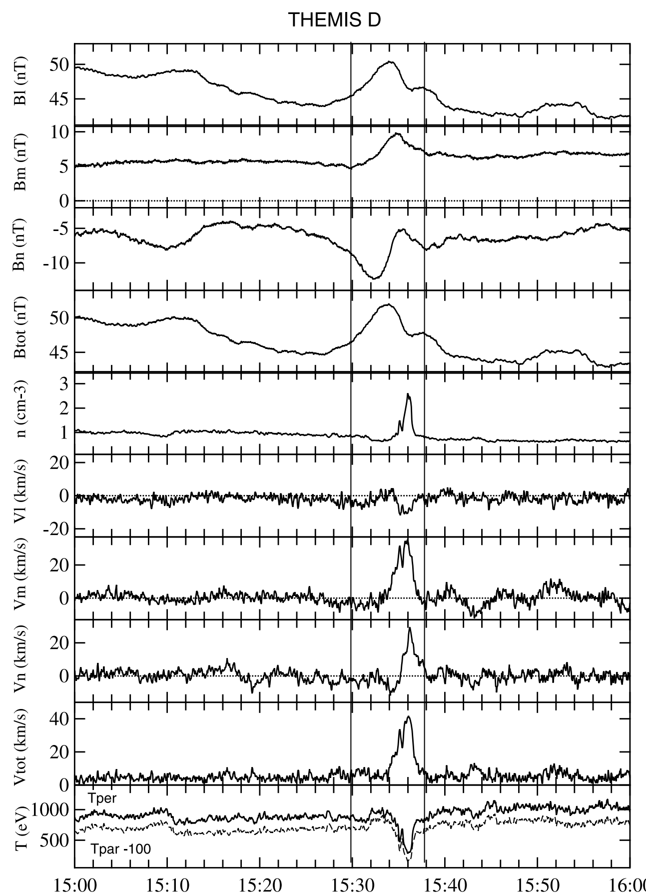

Figure 3. THEMIS D observations of plasma and magnetic field from 15:00 to 16:00 UT on 18 July 2008. The vertical lines bound the interval when the transient event was observed.

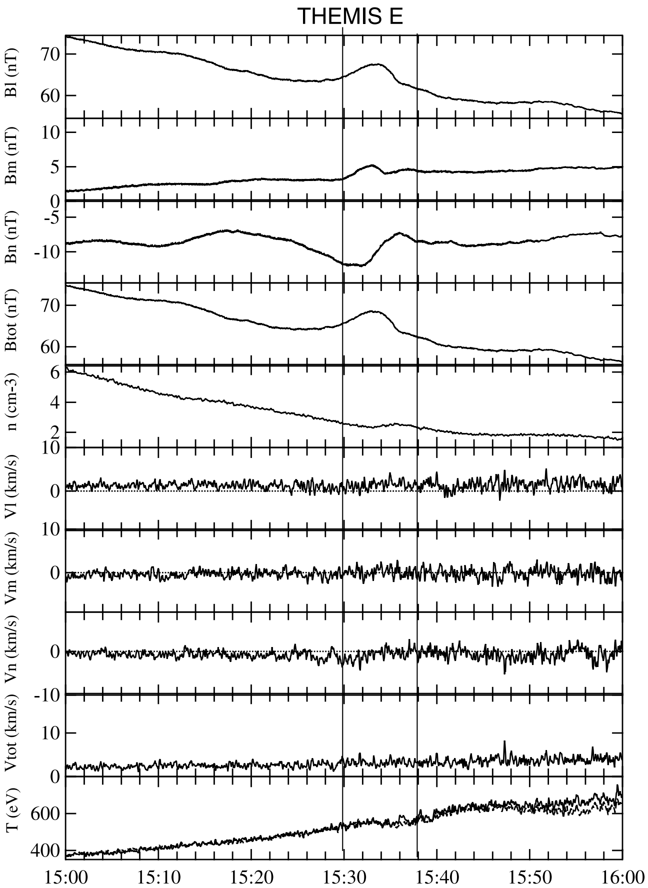

Figure 4. THEMIS E observations of plasma and magnetic field from 15:00 to 16:00 UT on 18 July 2008. The vertical lines bound the interval when the transient event was observed.

to D at 8.8 R_E was equal to ~160 km/s. Given the simplistic assumption that the event propagated through the magnetosphere and the magnetosheath with identical angular velocities, we rescaled this estimated velocity to 12 R_E and obtained a propagation velocity at the magnetopause of ~220 km/s. We can compare this flow velocity in the magnetosheath with the predicted gas dynamic model for the interaction of the solar wind and the magnetosphere presented by *Spreiter et al.* [1966]. For the observed solar wind velocity of 380 km/s, the predicted magnetosheath velocities at the local time of THEMIS D do not exceed 60 km/s. Therefore, the transient disturbance propagated duskward with a velocity greater than that of the magnetosheath plasma, i.e., as a fast mode wave through the magnetosheath.

[21] The motion of FTEs can also be inferred from the sense of the bipolar magnetic field perturbations that they generate in the magnetic field normal to the nominal magnetopause [*Rijnbeek et al.*, 1984; *Berchem and Russell*, 1984] and the flow perturbations that they generate opposite the direction of event motion in the ambient media [*Korotova et al.*, 2009]. All three THEMIS spacecraft observed (negative, positive) Bn signatures, indicating a southward component of event motion, opposite the magnetospheric magnetic field. THEMIS D and A observed 30–40 km/s flow velocities predominantly in the Vm direction and much smaller in the Vl direction. Magnetic field and plasma signatures expected in association with flux transfer events were discussed by *Korotova et al.* [2009]. Figure 5 presents the flow perturbations predicted for an event moving duskward on the magnetopause at a speed of −Vm that is greater than that of the ambient magnetosphere plasma. Spacecraft should observe −Vm velocities in the core of transient event but inward/outward (−,+) Vn and +Vm velocities on the flank of the event. Spacecraft that remain in the magnetosphere (D) observe inward/outward (negative, positive) velocities. Spacecraft that make direct encounters with the event (B) observe flows in the negative Vm direction throughout the encounter. The combined plasma and magnetic field observations at THEMIS A, D located on the flank of the event and THEMIS E situated far outside the event agreed and indicate an event moving predominantly duskward and slightly southward in the postnoon magnetosphere. *Sibeck and Smith* [1992] showed that the signatures predicted by FTE and boundary waves are similar unless the observing spacecraft enters the core region of an FTE or crosses the magnetopause.

[22] Geosynchronous observations of the disturbances associated with the transient events may be helpful in determining their origin. *Sibeck* [1993], *Korotova and Sibeck* [1995] and *Borodkova et al.* [1995] have presented case and statistical studies in which GOES observed compressions or expansions of the magnetosphere at the times of transient events. The GOES 10/11/12 observations presented in Figure 6 show three consecutive compressions of the magnetosphere within 1 h with maximum disturbances around 15:15–15:17 UT, 1531:30–15:34 UT and 15:49–15:50 UT. We relate the transient event observed by THEMIS at 15:34 UT to the second compression of the magnetosphere, which exhibited the strongest magnetic field strength enhancement of 2–4 nT in this sequence. The negative/positive variations in the Bz component indicates a southward component of event motion at the three locations. We estimated the azimuthal propagation velocity of the transient event between

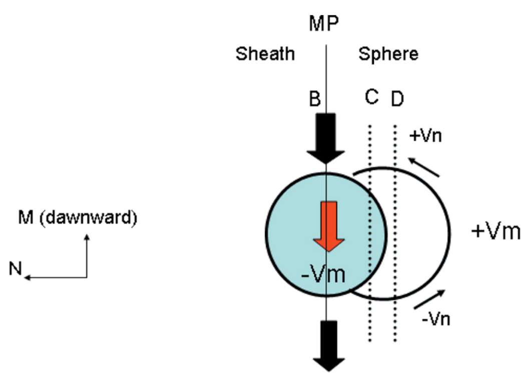

Figure 5. A transient event moving duskward on the magnetopause at a negative speed Vm (red arrow) that is greater than that of the ambient magnetosphere plasma. Plasma in front of the event is pushed forward, while that behind is entrained. The event pushes the surrounding plasma to the side, generating flows opposite to its motion on the flank. Letters B, C, and D mark the location of spacecraft relative to the transient event.

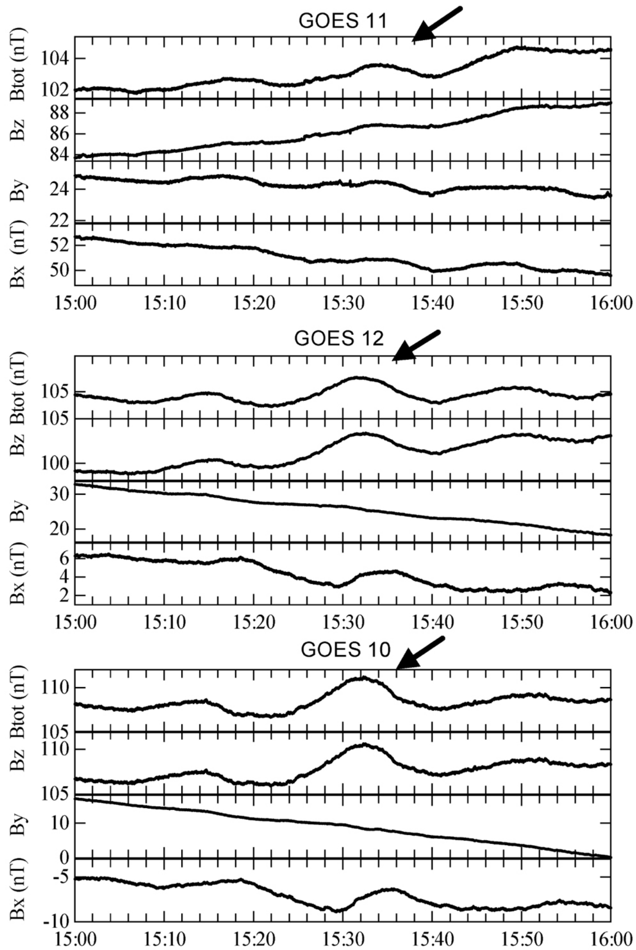

Figure 6. GOES 10/11/12 magnetic field observations in GSM coordinates from 15:00 to 16:00 UT on 18 July 2008. The arrows show the compression corresponding to the transient event.

the three GOES spacecraft by timing the occurrence of the peak magnetic field strengths. The event appeared first at prenoon GOES 12 at 15:31:33 UT and then propagated duskward and dawnward to be observed by GOES 10 at 15:32:18 and GOES 11 at 15:34:11 UT. Using the lag time and the azimuthal distance separating the spacecraft at 6.6 R_E we infer equatorial azimuthal propagation velocities of the transient event through the noon and prenoon magnetosphere of ~250 and 280 km/s, respectively. We rescaled the estimated velocities at 6.6 R_E to 12 R_E and obtained an azimuthal propagation velocities at the magnetopause of ~450 and 510 km/s. These velocities greatly exceed any expected for flow in the prenoon magnetosheath, leading us to conclude that the transient event propagated with the velocities of solar wind/foreshock discontinuities sweeping past the magnetopause rather than with the magnetosheath flow itself. The large velocity can be explained by the fact that a discontinuity striking the prenoon magnetopause would reach GOES 12, GOES 10, and GOES 11 nearly simultaneously, leading to high velocities.

[23] In search of solar wind triggers for the transient magnetospheric compressions we inspected THEMIS B and C observations for corresponding signatures. As indicated in Figure 1, THEMIS C moved in the postnoon magnetosheath from GSM (X, Y, Z) = (15.42, 2.67, −6.40) R_E to (15.77, 3.48, −6.43) R_E from 15:00 to 16:00 UT. The plasma and magnetic field observations presented in Figure 7 showed a sequence of bow shock motion back and forth across the locations of THEMIS C. Vertical lines bound the intervals when THEMIS C was in the solar wind. The sheath intervals are characterized by a velocity of 0–100 km/s, density of 10–20 (cm^{-3}), and magnetic field strength of 10–20 nT. The solar wind intervals are characterized by a velocity of 300–370 km/s, density of 0–5 (cm^{-3}), and magnetic field strengths of 0–5 nT. Figure 8 presents THEMIS C ESA ion and electron energy flux spectrograms from 15:00 to 16:00 UT. They also clearly show the sequence of bow shock motions. The solar wind intervals are characterized by colder (narrower) ion and electron distributions than those in the magnetosheath.

[24] THEMIS C observed density increases at 15:30 UT and 15:48 UT preceding two intervals in the solar wind. There were also density peaks on returns to the magnetosheath

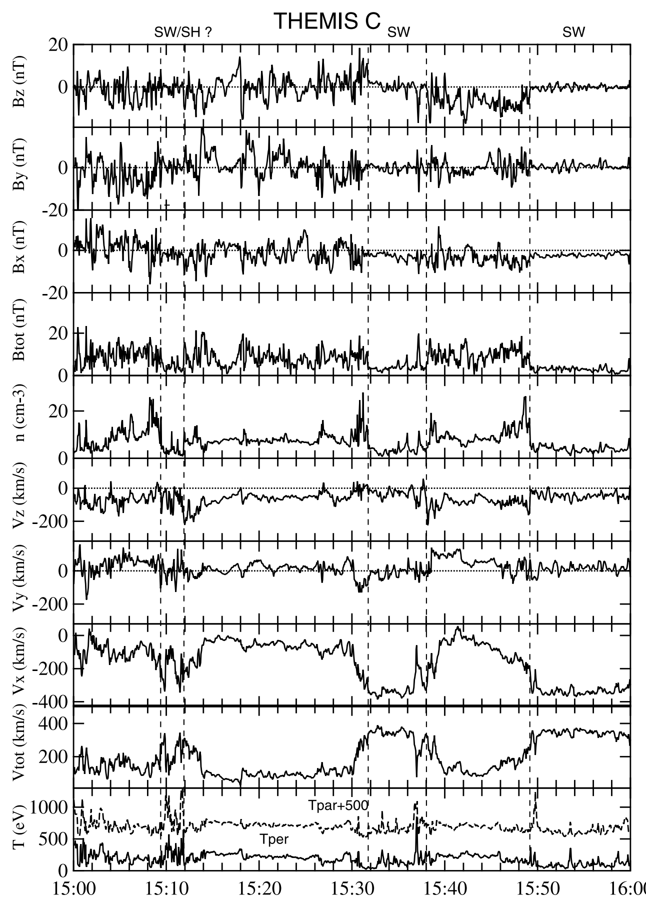

Figure 7. THEMIS C observations of plasma and magnetic field from 15:00 to 16:00 UT on 18 July 2008. From top to bottom, the GSM Bz, By, Bx components, total magnetic field, the ion density, Vz, Vy, Vx components of velocity in GSM coordinates, total velocity, and the ion temperatures perpendicular and parallel to magnetic field are shown. Vertical lines indicate the intervals when THEMIS C was in the solar wind.

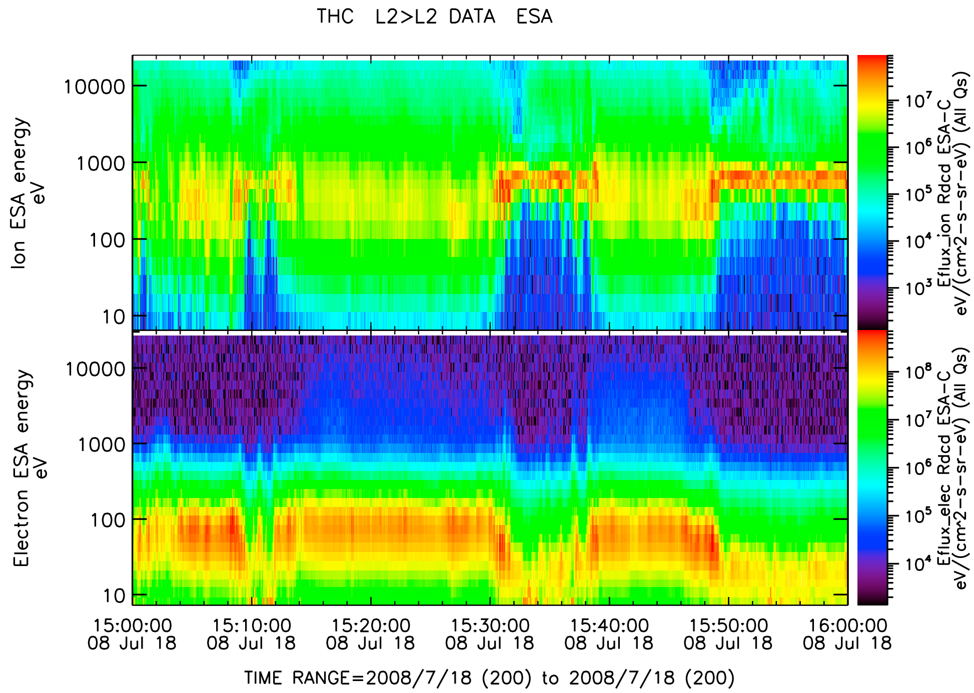

Figure 8. Energy flux spectrograms for electron and ions in the range of energies from 2 eV to 25 keV (ESA) observed by THEMIS C from 15:00 to 16:00 UT on 18 July 2008.

proper at 15:12 and 15:38 UT. The spacecraft also observed a spike of density at 15:08 UT preceding a region characterized by a low magnetic field strength (2–4 nT), low densities (2 cm^{-3}), high temperature (400 eV) and low velocity (120 km/s). As the properties of the latter region are not strictly consistent with either the solar wind (velocities too low, temperatures too high) or the magnetosheath (density and magnetic field strength too low), we believe this interval was either a foreshock cavity or its signature downstream in the magnetosheath. The enhancements and decreases of density attending the bow shock motion suggest that the motion resulted from variations in the solar wind density/pressure.

[25] Then we examined observations of THEMIS B located upstream from the postnoon bow shock, moving sunward in the solar wind from GSM (X, Y, Z) = (24.45, 2.55, −9.78) R_E to (24.83, 3.35, −9.73) R_E from 15:00 to 16:00 UT (Figure 1). Figure 9 shows the THEMIS B GSM longitude and latitude, cone angle, GSM Bx component and B total magnetic field, plasma observations in GSM coordinates. The IMF was often nearly radial and ecliptic and always very disturbed during the interval studied and therefore was favorable for the formation and elimination of the foreshock in the subsolar region in response to fluctuating magnetic field orientations connecting and disconnecting with the bow shock.

[26] We identified three possible but weak upstream signatures related to the compressions of the magnetosphere and bow shock motion. Dashed lines bound the intervals with these features on the Figure 9. The first interval from 15:06 to 15:10 UT is marked by a cavity with a decreased density, an increased temperature and fluctuation in the IMF strength and orientation. The IMF cone angle on the trailing edge of this cavity increased from ~1° to 87°. The density and magnetic field strength increased during the second interval from 15:28 to 15:30 UT and the magnetic field strength and cone angle continued to fluctuate. During the third interval from 15:46 to 15:48 UT THEMIS B observed an azimuthal rotation of the magnetic field without any notable plasma signatures. If there are signatures in the solar wind at THEMIS B for the compressions, then they are not very pronounced or systematic.

[27] Though the solar wind density and corresponding pressure variations associated with these features were modest, the fluctuating IMF could have caused much more substantial variations in the solar wind dynamic pressure applied to the magnetosphere via interactions in the foreshock. *Fairfield et al.* [1990] indicated that even in the presence of a solar wind that is absolutely steady in velocity and density but which carries an imbedded interplanetary magnetic field of variable orientation, there will be variations in the pressure exerted on the magnetopause. We sought evidence that the density variations observed at THEMIS C originated in the foreshock. *Fairfield et al.* [1990] showed that the magnetic field strength and density perturbations in the foreshock are highly correlated whereas these quantities tend to be anti-correlated in the undisturbed solar wind. Figure 10 presents the spectra of ions, the density, total magnetic field strength and perpendicular temperature observed by THEMIS C from 15:28 to 15:40 UT on a larger scale. The observations indicate that the marked density spikes exhibited a very clear correlation with the increases in magnetic field strength and therefore were produced in the foreshock and not inherent to the solar wind.

[28] To determine when THEMIS C was in foreshock we inspect the ion energy flux spectrogram. As noted by *Fairfield et al.* [1990], the presence of suprathermal particles

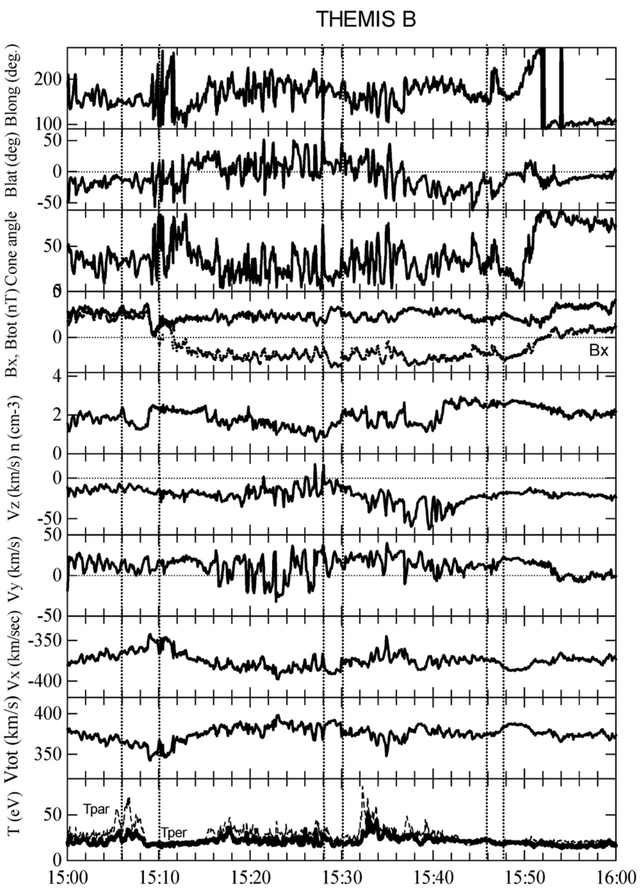

Figure 9. THEMIS B observations of magnetic field and plasma from 15:00 to 16:00 UT on 18 July 2008. From top to bottom GSM longitude, GSM latitude, cone angle, GSM Bx component and total magnetic field strength, the ion density, Vz, Vy, Vx components of velocity in GSM coordinates, total velocity, and the ion temperatures perpendicular and parallel to magnetic field are shown. Vertical lines mark the intervals with varying magnetic field and plasma parameters.

is a good indicator of the foreshock. Figure 8 shows that particles with energies ≥10 keV were present at all times when THEMIS C was in the solar wind with the exception of three intervals from 15:08 to 15:10 UT, from 15:31:50 to 15:32:45 UT, and from 15:48 to 15:55 UT. Each disappearance of the energetic particles indicates a change in the IMF direction that reconfigured and eliminated the foreshock from the subsolar region. We claim that the motion of the foreshock away from the subsolar region produced the compressions of the magnetosphere and triggered the transient events observed by THEMIS. *Thomas and Brecht* [1988] and *Fairfield et al.* [1990] have shown that kinetic processes within the foreshock excavate cavities and generate density variations at the edge of the foreshock. When the foreshock moves away from subsolar bow shock, the subsolar magnetosphere absorbs the full impact of the oncoming solar wind and becomes more compressed. *Korotova et al.* [2004] have demonstrated that the interaction of foreshock with the bow shock was the cause of a transient event observed in high-latitude ground magnetograms.

[29] Since we believe that we have identified bow shock and possibly solar wind signatures associated with our transient magnetospheric event, we should examine pressures in all three regions. Figure 11a shows magnetic, thermal and total ion pressures observed by THEMIS D. The three increases in the magnetic field pressure (at 15:11, 15:34 and 15:55 UT) correspond to the three compressions of the magnetosphere observed by GOES (see discussion of Figure 6). The total pressure increased from 0.9 to 1.2 nPa while the thermal pressure decreased slightly inside the most prominent transient event at 15:34 UT. This enhancement is less than that for FTEs reported by *Paschmann et al.* [1982] for which the sum of plasma pressure and magnetic pressure inside the events was typically twice as large as that outside the event. The difference presumably results from the fact that this event was observed deeper in the magnetosphere, some 4 R_E from the nominal magnetopause.

[30] Figure 11b presents magnetic, thermal and total ion pressures observed by THEMIS C. The thermal pressure dominated in the magnetosheath where it ranged from 0.2 to 0.7 nPa. As noted earlier, enhancements in the total pressure bounding crossings into the solar wind indicate that pressure increases pushed the bow shock inward and compressed the magnetosphere. A decrease in temperature accompanied the enhanced density from 15:30 to 15:31 UT, resulting in only a modest thermal pressure increase.

[31] Based on the observations in Figure 11b, we expect to find enhanced solar wind dynamic pressures at the times

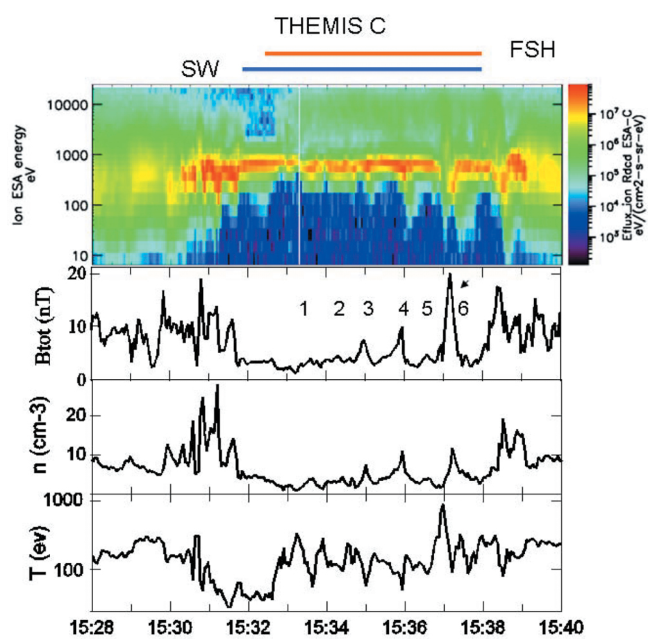

Figure 10. An expanded view of the THEMIS C observations from 15:28 UT to 15:40 UT on 18 July 2008. From top to bottom, the energy flux spectrogram for ions in the range of energies from 2 eV to 25 keV (ESA), total magnetic field strength, and ion density and perpendicular temperature of plasma are shown. The blue and red bars at the top show the intervals when THEMIS C was located in the solar wind and foreshock. Numbers indicate a sequence of correlated pulses in the foreshock.

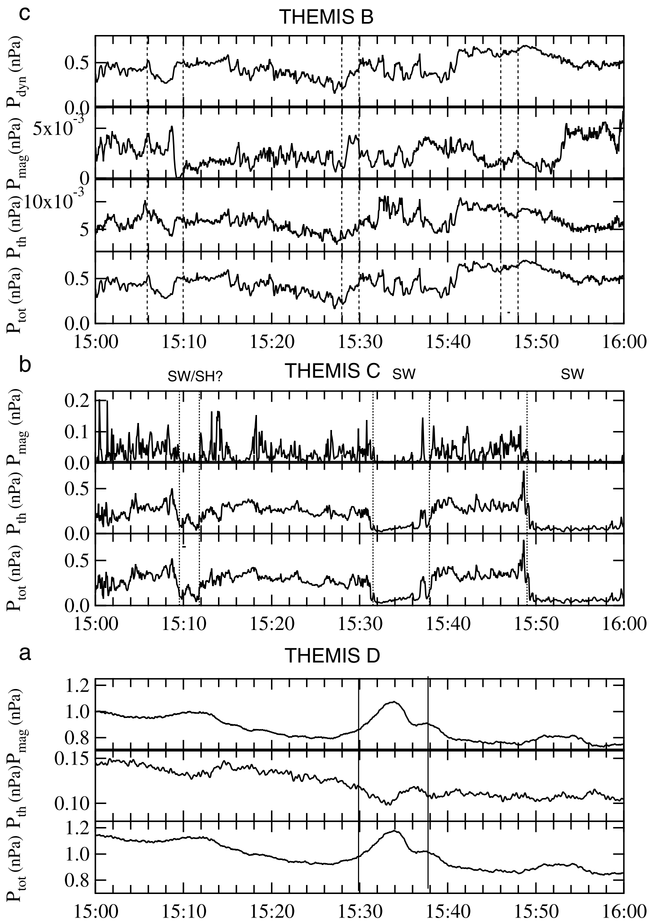

Figure 11. (a and b) Magnetic, thermal and total pressures for THEMIS D and C. (c) Dynamic, magnetic, thermal and total pressures for THEMIS B from 15:00 to 16:00 UT on 18 July 2008.

of the three events. Figure 11c present dynamic, magnetic, thermal and total ion pressures of the solar wind observed by THEMIS B. The total pressure varied from 0.16 to 0.69 nPa. It was dominated by the dynamic pressure while the sum of magnetic and thermal pressures played a minor role and did not exceed 0.01 nPa. THEMIS B observed an abrupt increase in dynamic pressure at 15:09 UT, a gradual increase from 15:28 to 15:30 UT and only a very weak increase from 15:46 to 15:48 UT. Since the THEMIS B solar wind observations do not fully explain the THEMIS C bow shock crossings or the transient events in the magnetosphere, we must also invoke the foreshock related effects observed by THEMIS C to explain these phenomena.

[32] The transient event was associated with a density increase and bow shock motion and it is unlikely that the event was an FTE. Its duration was long compared to typical FTEs and it was observed deeper within the magnetosphere than the locations where FTEs are typically observed. The IMF orientations for which it occurs were highly variable and not strongly southward. The strong duskward and only slightly southward motion inferred from the THEMIS spacecraft indicates a duskward moving boundary wave rather than the north-south motion expected for an east-west oriented FTE moving northward or southward. We ruled out an explanation of the transient event in the terms of the Kelvin-Helmholtz instability as the solar wind velocity is low and the event did not occur on the flanks of the magnetosphere.

[33] In summary, the above observations indicate that the transient event was an impulsive event produced by the compression of the magnetosphere in the result of interactions of the solar wind, foreshock and bow shock.

4. Ground-Based Observations

[34] Abrupt variations in the solar wind density (and dynamic pressure) have frequently been invoked to explain isolated transient events in the dayside magnetosphere and high-latitude ionosphere [e.g., *Friis-Christensen et al.*, 1988; *Sibeck*, 1990]. The solar wind flow sweeps the density variations into the bow shock, where they launch fast mode waves that propagate through the magnetosheath. Once they strike the magnetopause, the pressure fronts launch fast and intermediate mode waves into the magnetosphere [*Tamao*, 1964]. The fast mode waves propagate across magnetic field lines to produce transient events in the equatorial magnetosphere, whereas the intermediate mode waves propagate along magnetic field lines to produce transient events in the high-latitude dayside ionosphere [*Southwood and Kivelson*, 1990; *Glassmeier and Heppner*, 1992]. Variations in the pressure driven by solar wind features may produce disturbances on the magnetopause that have global extent. In agreement with the predictions of pressure pulse model of *Sibeck* [1990], *Korotova et al.* [2002] showed a sequence of transient events observed in high-latitude magnetograms that were global.

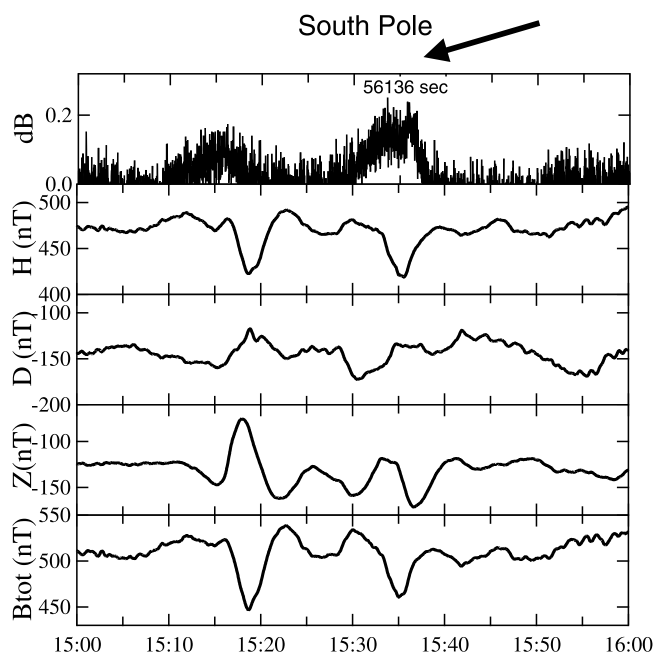

Figure 12. Riometer and magnetic field observations from South Pole station ($\Phi = -74.0°$, $\Lambda = 16.4°$, MLT = UT − 03:30) from 15:00 to 16:00 UT on 18 July 2008. The arrow shows the riometer and ground magnetometer responses to the most prominent compression of the magnetosphere.

[35] To identify ground signatures produced by the most prominent compression of the magnetosphere and determine their special extent, we examined magnetic field traces from more than 40 ground observatories in the Northern and Southern Hemispheres. We found that the surface magnetic field displayed transient disturbances with monopolar or bipolar variations between 15:35 and 15:47 UT that were quite widespread in latitude and longitude and whose precise features depended on their location.

[36] Figure 12 presents riometer and magnetic field observations from the high-latitude South Pole station, which was located near local noon. The two transient events at 15:18:27 and 15:35:30 UT correspond to the GOES and THEMIS compression events. South Pole observes no signature corresponding to the third, weakest, compression of the magnetosphere. The 15:35:30 UT event exhibits bipolar positive/negative variation in the Z component and monopolar negative variation in the H component with an amplitude of ~60 nT that was accompanied by a slight increase in riometer absorption. The impulsive precipitation of energetic electrons is rather common during magnetic impulsive events [*Korotova et al.*, 1999].

[37] Then we inspected ground magnetograms at prenoon and local morning hours. At most stations the transient event exhibited long-lasting (~10–15 min) monopolar variations in D and H components with amplitudes of 5–20 nT associated with a sequence of compressions of the magnetosphere during the interval studied. To determine the direction of

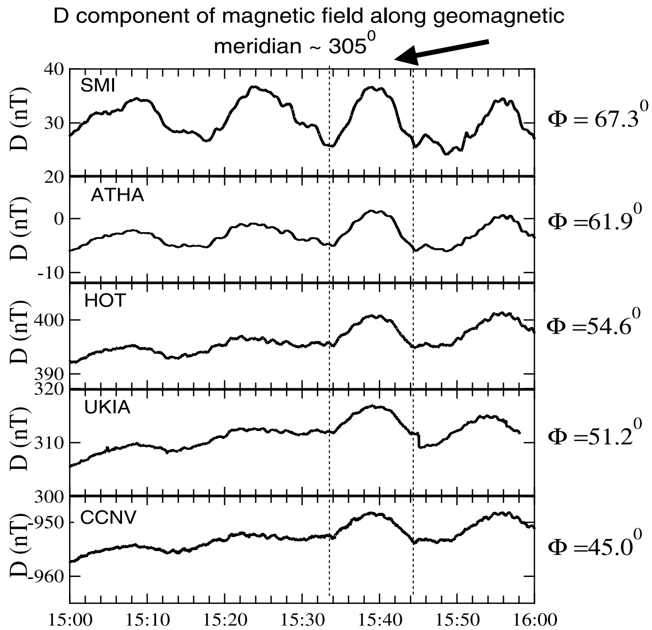

Figure 14. D components of magnetic field observed by five Canadian stations along geomagnetic meridian $\Lambda = 305°$. Dashed lines bounded the ground response to the most prominent compression of the magnetosphere.

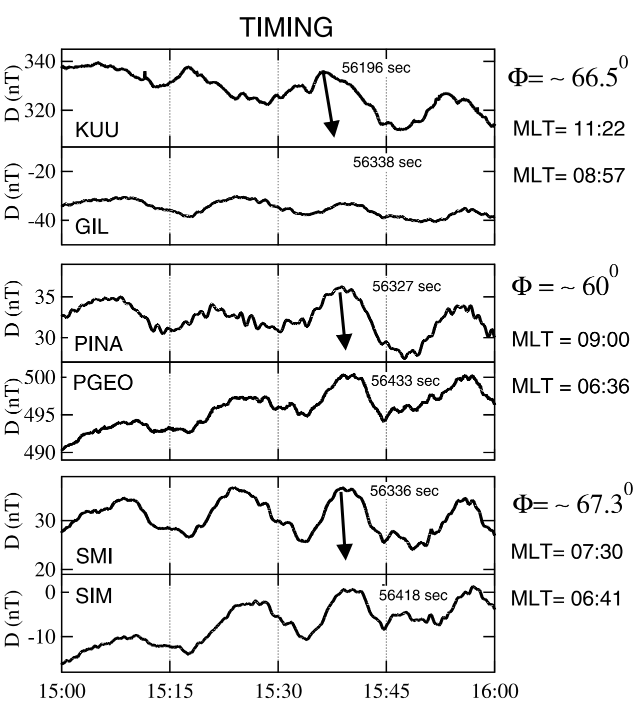

Figure 13. The D component of magnetic field at three couples of Canadian stations from 15:00 to 16:00 UT on 18 December 2008. The geomagnetic latitude for each pair of stations and the local magnetic time for the occurrence of the transient event are given. The arrows indicate the dawnward direction of propagation of the transient event between two stations in each couple.

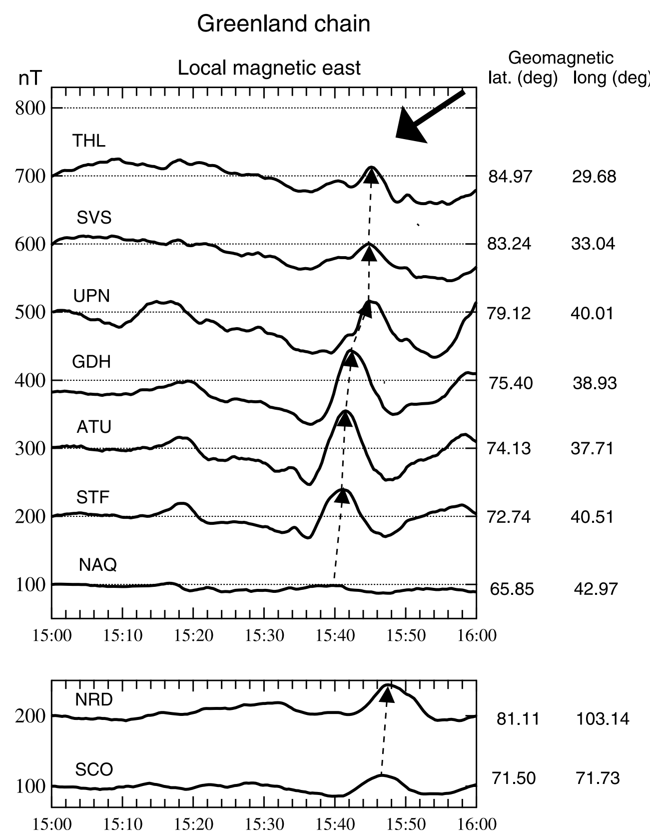

Figure 15. Eastward components of the Greenland east and west coast magnetograms from 15:00 to 16:00 UT on 18 July 2008. The geomagnetic latitude and longitude for each station are given.

propagation and estimate the azimuthal velocity of the variations corresponding to the transient event studied we used magnetic field data from three pairs of Canadian stations, selected at similar geomagnetic latitudes but separated in longitude and timed the occurrence of peak variation at each station. Figure 13 presents the D component variations at these stations, which were better defined than the H component variations. The geomagnetic latitude for each pair of stations and the local magnetic times for the occurrence of peak variation at each station are also given. Arrows between ground stations indicate the azimuthal direction of propagation of the variations in the high-latitude and midlatitude ionosphere. Close inspection of the magnetic field records showed that the 15:34 UT transient event moved dawnward at a velocity of 7–19 km/s and its latitudinal extent was rather large. Figure 14 presents the transient variation observed at latitudes of Φ = 45°–67.3° at 15:38:56 UT (at ~07:30 MLT) that propagated dawnward as a whole structure without delays at any latitude.

[38] Inspection of magnetic field observations from the east and west coast Greenland stations that map to the early postnoon and afternoon sectors of the magnetosphere shows that the transient event produced by the compression of the magnetosphere was observed at all stations around 15:42 UT.

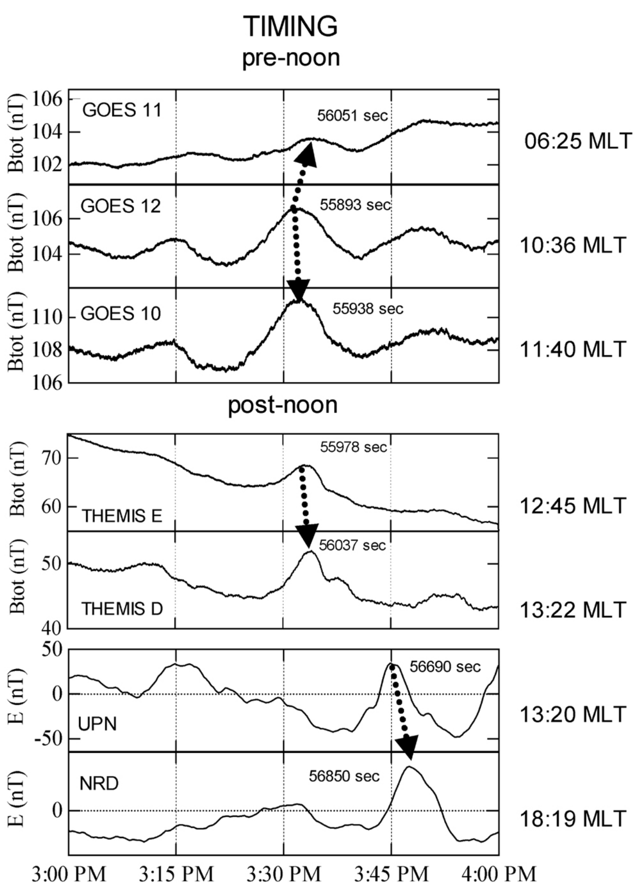

Figure 16. Time sequence of occurrence of transient event observed in the magnetic field by GOES 12, GOES 10, THEMIS E, GOES 11, THEMIS D, and by Greenland stations UPN and NRD from 15:32 to 15:47 UT on 18 July 2008.

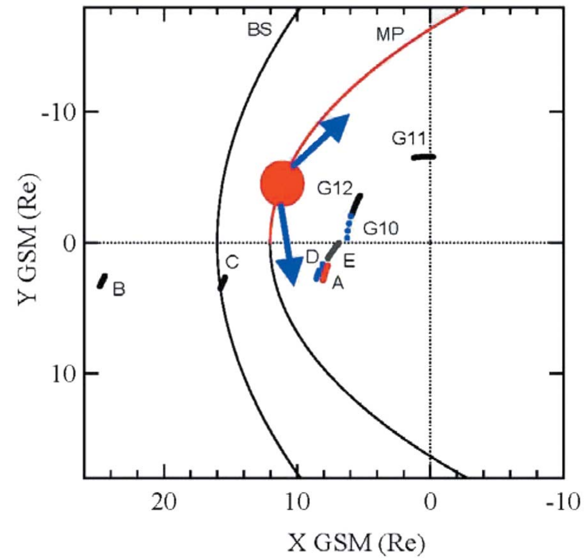

Figure 17. Locations of THEMIS and GOES 10/11/12 spacecraft in the GSM X-Y and X-Z planes from 15:00 to 16:00 UT on 18 July 2008. Arrows show the dawnward and duskward directions of propagation of the transient event from its source (red circle) on the magnetopause.

Figure 15 shows their D components and the geomagnetic latitude and longitude for each station. The transient event exhibited a negative/positive variation in the H component (not shown) and monopolar positive variation in the D component that reached maximum amplitudes of 110–130 nT at latitudes from Φ = 74° to 76° at early postnoon hours. It propagated northward at a velocity of ~3–4 km/s and duskward at a velocity of ~3.5–7.5 km/s. We note that the amplitude of the transient event observed in the Southern hemisphere at South Pole station was much weaker than at close conjugate Greenland stations which can be explained by lower conductivity in the southern (winter) ionosphere.

[39] Inspection of the ground magnetograms revealed that South Pole recorded the transient event first among the ground stations; therefore, we can conclude that the event originated close to local noon and propagated both dawnward and duskward. Figure 16 summarizes the timing results for the transient event observed at GOES 12, GOES 10, GOES 11, THEMIS E, THEMIS D, and Greenland stations UPN and NRD. As GOES 12 observed the transient event first we could conclude that the transient event originated in the prenoon hours. Figure 17 shows schematically the dawnward and duskward directions of propagation of the transient event from its source (red circle at prenoon local times).

5. Summary and Conclusions

[40] We presented a case study of simultaneous multipoint spacecraft and high and midlatitude ground magnetometer observations of a long-lasting transient event that occurred on a quiet day at 15:34 UT on 18 July 2008. We sought to determine whether this event was an FTE produced by unsteady merging or an impulsive event caused by other mechanisms. Located in the outer magnetosphere,

THEMIS A, D and E observed a transient event marked by a bipolar (negative, positive) signature in the Bn component and a ~5–7 nT enhancement in the magnetic field strength. Plasma flows and the bipolar perturbations observed during the event indicate that it moved primarily duskward and slightly southward in the early postnoon magnetosphere.

[41] The transient event was one of the three magnetospheric compressions observed by the three GOES spacecraft and THEMIS A, D and E. THEMIS C located near the bow shock, observed a sequence of density increases, inward bow shock motions, and exits from the foreshock at the times corresponding to each of these magnetospheric compressions. THEMIS B, in the solar wind, observed less clear signatures: weak or gradual increases in the solar wind dynamic pressure for some of the events.

[42] We concluded that foreshock effects associated with varying quasi-radial IMF directions and solar wind pressure increases caused the bow shock and magnetopause motions, compressed the magnetosphere and triggered the transient event. The transient event corresponded to an impulsive event with either monopolar or bipolar signatures in each of 40 high and midlatitude ground magnetograms. Timing studies indicated that these signatures moved dawnward prior to local noon and duskward at noon and postnoon.

[43] The directions of propagation, inferred from the spacecraft and ground observations, the flow patterns, surrounding the events and its global spatial extent indicate that the transient event was not an FTE, but rather an impulsive event corresponding to an MIE in ground magnetograms.

[44] It is important to note that the presence of THEMIS C near the bow shock enabled us to find a clear correlation of pressure variations and the compressions of the bow shock and magnetosphere, making possible the interpretation in terms of pressure pulses. Without these observations we could have misinterpreted the source of the transient event based on the observations of the solar wind and IMF made by THEMIS B. These findings confirm that multiple satellite observations in right locations are essential to understanding of the solar wind–magnetosphere interaction.

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V. Angelopoulos, IGPP, ESS, UCLA, Los Angeles, CA 90095-1567, USA.

G. I. Korotova, Computer and Space Sciences Building, Institute for Physical Science and Technology, University of Maryland, College Park, MD 20740, USA. (gkorotov@umd.edu)

D. G. Sibeck, NASA GSFC, Code 674, Greenbelt, MD 20771, USA.

V. Styazhkin, IZMIRAN, Troitsk, Moscow Region, 142190, Russia.

A. Weatherwax, Department of Physics and Astronomy, Siena College, 515 Loudon Rd., Loudonville, NY 12211-1462, USA.